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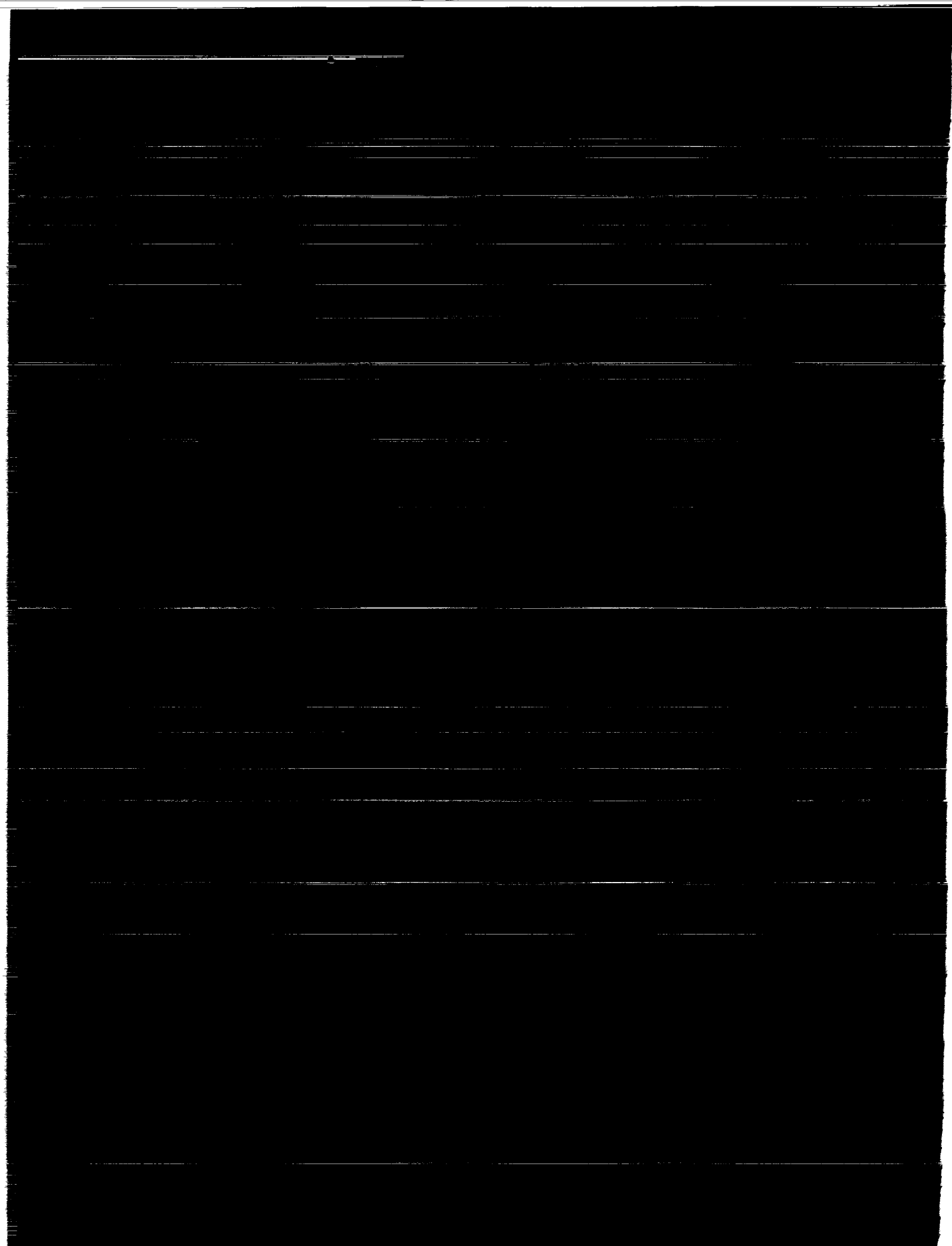
Development of the Seeding System Used for Laser Velocimeter Surveys of the NASA Low-Speed Centrifugal Compressor Flow Field

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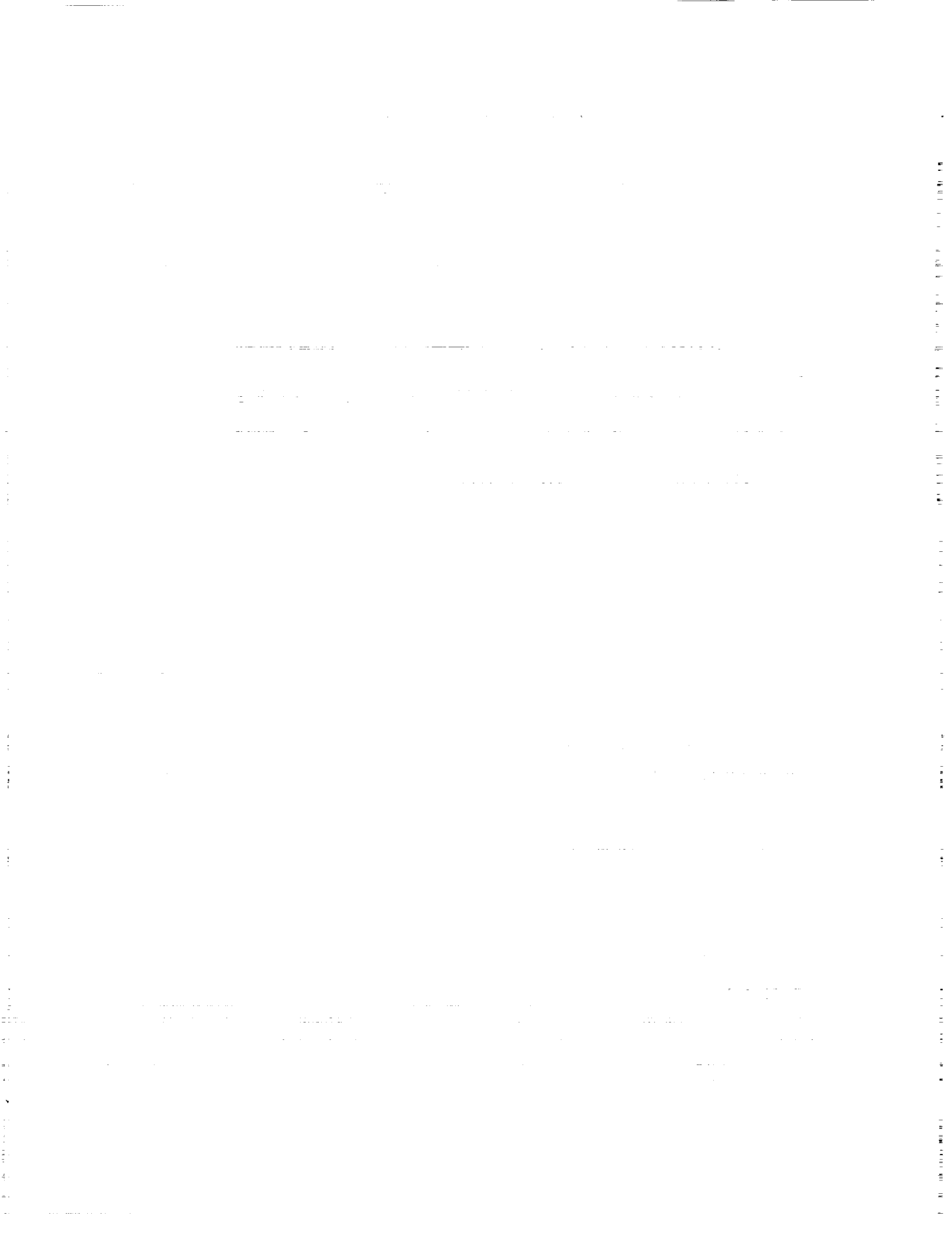
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Summary

An atomizer-based system for distributing high-volume rates of seed material was developed to support laser velocimeter investigations of the NASA Low-Speed Centrifugal Compressor flow field. This report describes the seeding system and the major concerns that were addressed during its development. Of primary importance were that the seed material be dispersed as single particles and that the liquid carrier used be completely evaporated before entering the compressor.

Introduction

The Low-Speed Centrifugal Compressor (LSCC) facility at NASA Lewis Research Center was built to obtain detailed flow-field measurements for computational fluid dynamic code assessment and flow physics modeling in support of advanced small gas turbine engine technology. Among the instrumentation selected was a laser velocimeter that optically measures the instantaneous velocity of light-scattering particles suspended in the flow field. It is important, therefore, that the particles be small enough to follow the airflow. However, the amount of light scattered from the particles, and thus, the signal-to-noise ratio, decreases with the square of the particle diameter. A compromise is required, and the present state-of-the-art, optimum particle size, between 0.5 to 1.0 μm in diameter, ensures that the particle will be large enough to measure but small enough to follow the flow closely. Other considerations for developing the seeding system were that the seed material be dispersed as single particles and that any liquid carrier used for the seed material be fully evaporated before reaching the laser probe volume.

Available commercial seeding systems generally deliver either very large particles (atomizer-based fogger) or ones that are too small for detection by the laser velocimeter used for this program (smoke-based systems). Furthermore, existing seeding systems developed for disbursing seed particles in rotating machinery with small annulus areas do not provide for the volume rate of seed material required in the

large annulus area of the LSCC. This report describes the seeding system developed for use in the LSCC facility, the modifications that were made, and the testing that resulted in the final adjustable seeding system configuration. Considerations for the seeding material and droplet size were also addressed.

Facility and Seeding System

The major elements of the Low-Speed Centrifugal Compressor (LSCC) facility are shown in figure 1. Air is drawn into the plenum through a bank of flow straighteners from a filtered vent in the roof. The flow then enters the bellmouth, passes through the compressor, and exits through the throttle valve into the volute collector and into the exhaust line. The 5-ft- (1.52-m-) diam compressor has 20 blades and design operating conditions of 66 lb/s (30 kg/s) flow rate and 1920 rpm speed. Three windows installed in the shroud provide optical access to the flow field. A complete description of the facility is provided by Wood et al. (ref. 1). The laser Doppler velocimeter (LDV) system that was used in the research program consisted of an argon-ion laser, coupled with appropriate optics, to yield a two-component laser fringe velocimeter operating in on-axis backscatter mode. A complete description of the laser system is provided by Hathaway et al. (ref. 2).

Figure 2 is a schematic of the laser and its seeding system. Compressed air was used to pressurize two 5-gal (19-l) tanks filled with a liquid carrier and the seed material. The tanks delivered the mixture under pressure to a set of commercially available nozzles (two for each tank) where another line of compressed air acted to atomize the mixture into the plenum. A third line of compressed air was used to mechanically turn the nozzles on and off with a needle valve built into the nozzles. The needle valve was considered an important feature of the commercial nozzle because it provided a means of dislodging seed material from the nozzle.

The fasteners on the bars and guy wires were adjustable so that the nozzles could be located anywhere in the plenum to meet the area and density requirements of the test in progress.

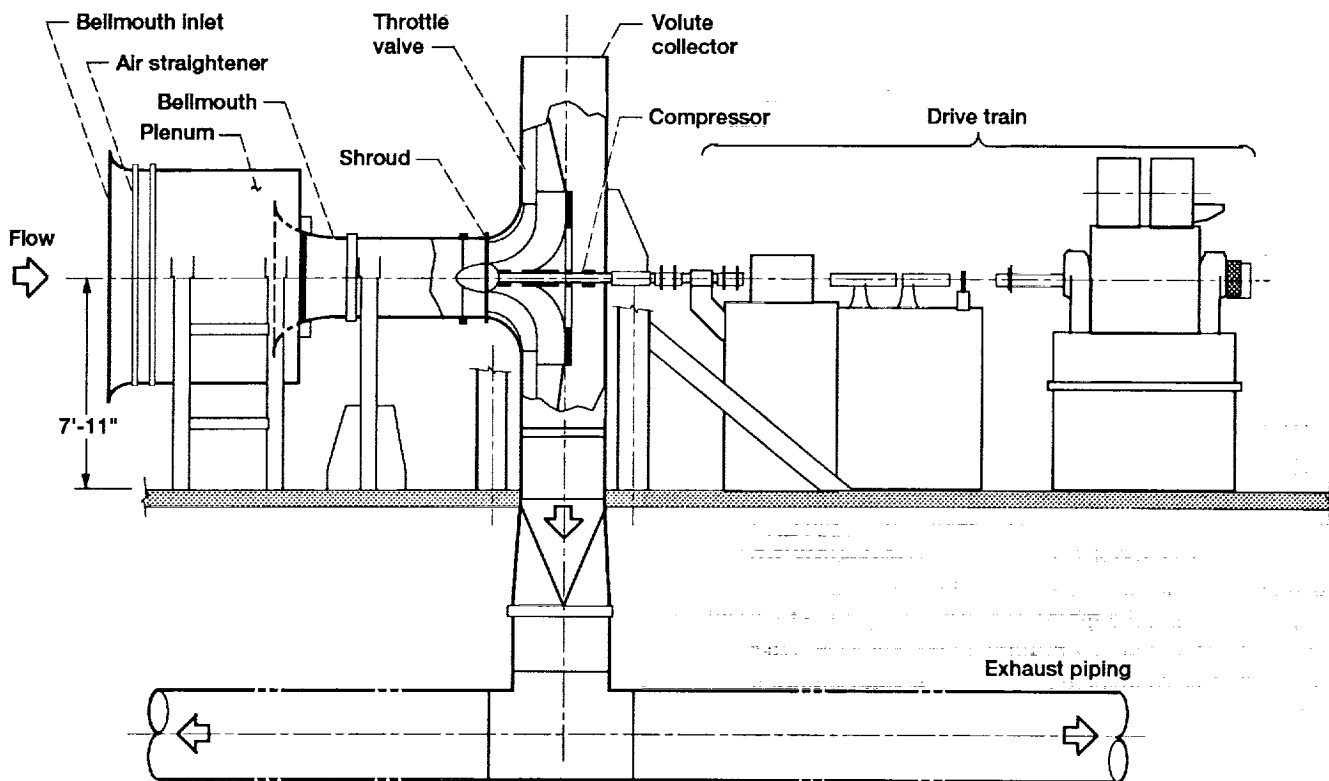


Figure 1.—The NASA Low-Speed Centrifugal Compressor (LSCC) facility.

Flexible tubing was used in the plenum from the nozzles to the plenum wall. Metal tubing was used from the plenum to the two external 5-gal (19-l) tanks. Solenoid valves in the system automatically deactivate the nozzles in an emergency shutdown. At shutdown, pressure in the lines was vented into the collector. Originally, the air and liquid switches operated all the nozzles simultaneously. A later modification allowed the nozzles from each tank to be operated independently.

The atomized liquid mixture evaporated as it traveled from the plenum to the test section. The particles that were contained in the droplets remained in the flow, and their velocity was measured with the laser velocimeter. A laser-based aerodynamic particle detector (ref. 3) was used during the check-out phase to determine sphere size and distribution of the seeding flow as it entered the compressor. The particle detector collected the flow samples through a 10-ft (3-m) length of 0.25-in. (6-mm) flexible tubing connected to a 0.25-in. (6-mm) Pitot tube located just forward of the compressor inlet.

Initial Considerations

Obtaining good laser velocimeter data depended on developing small, uniform-size seed particles and dispersing the seed material as evenly as possible throughout the flow passage. Thus, the requirements for the LSCC program were as follows:

- (1) Seed particles should be uniform in size and about $1\text{ }\mu\text{m}$ or less.
- (2) Dispersion of seed material should contain only single particles.
- (3) The liquid carrier must be fully evaporated before entering the test section.
- (4) The liquid carrier should be as inexpensive and as nontoxic as possible.

Some previously used seeding materials and spray devices have not provided uniform and accurate particle sizes for laser experiments. Polystyrene latex (PSL) was chosen for this program because it is an inert solid substance that is buoyant, has a high index of refraction, and can be manufactured as very small, precise-diameter spheres with near perfect reproducibility. The manufacturing process was developed by Nichols (ref. 4). When manufactured, the polystyrene spheres were suspended in about 90 percent water by volume. From a health standard, PSL becomes a nuisance at levels of 15 g/m^3 and an anesthetic (irritant) at 1.1 percent of the volume. Throughout the LSCC project, the amount of PSL used with the liquid carrier was below the Lower Exposure Limit (LEL) recommended by the American Conference of Governmental Industrial Hygienists (ACGIH) (ref. 5).

Water and ethyl alcohol were considered for use as the liquid carrier for the polystyrene spheres because neither dissolves polystyrene. Although it is less expensive, methyl alcohol was not used because it dissolves PSL, is more toxic

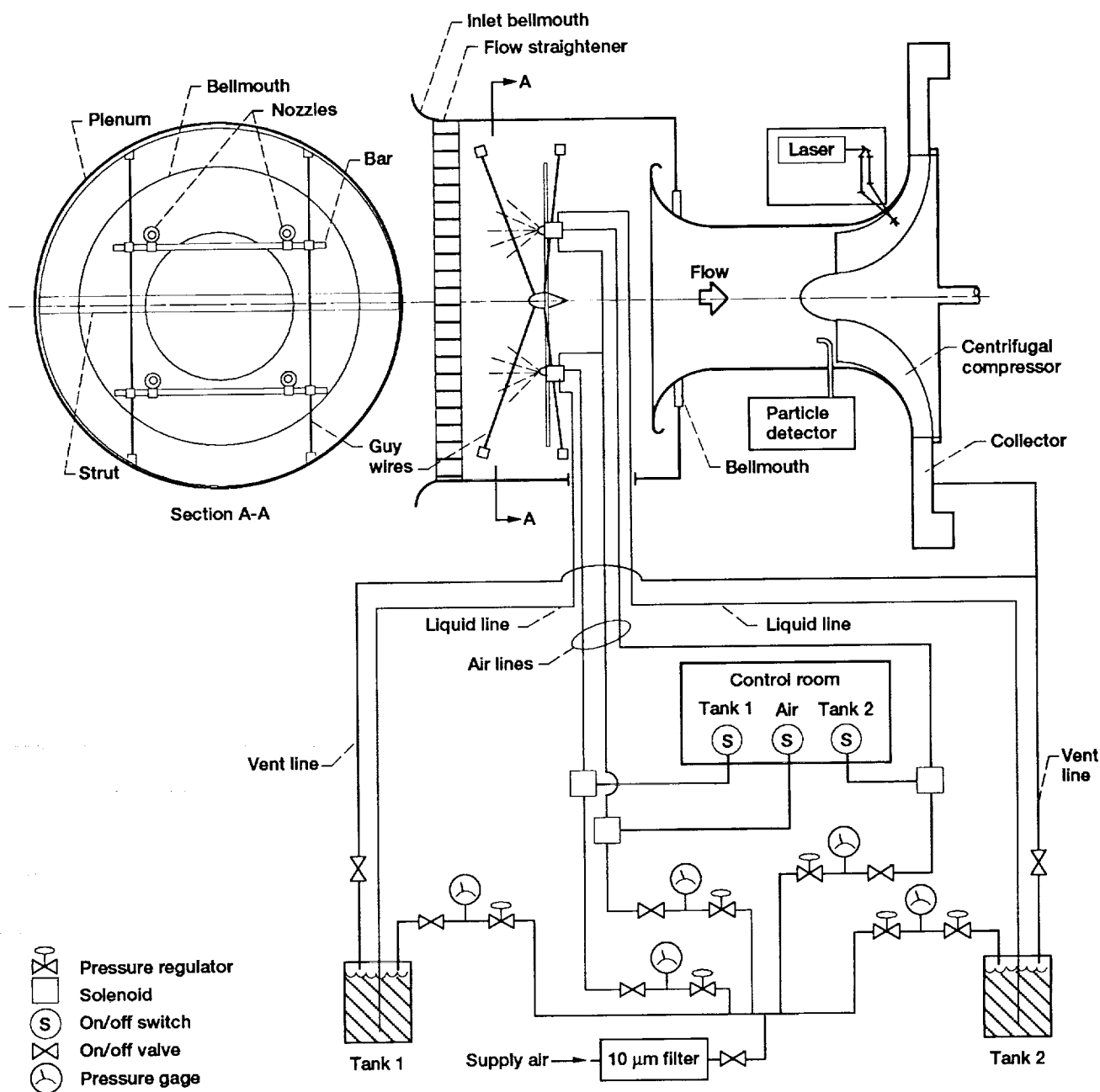


Figure 2.—The laser and schematic of seeding system.

(ref. 5), and has a higher vapor pressure. Although water is less expensive and nonhazardous, and therefore, most desirable, it does not evaporate rapidly enough. Pure ethyl alcohol was determined the best choice for the liquid carrier because of its better evaporation properties. The mixture ratio of polystyrene solution to that of ethyl alcohol was less than 0.1 percent by volume.

Since ethyl alcohol is an anesthetic, certain procedures had to be followed to ensure the safety of those working with the seeding system. If the spray nozzle system was located in front of the bellmouth inlet and air straightener (fig. 1), the

alcohol vapors would contaminate the atmosphere in the cell. Safety considerations, therefore, required that an alcohol detector be located in the cell to verify that the percent of alcohol in the atmosphere was ventilated below the LEL before personnel could work in the cell. In addition to alcohol contamination, the PSL seed particles would accumulate on the flow straighteners and would, in time, block part of the flow. Cleaning the flow straightener would be very time consuming. If the spray nozzles were located in the plenum, all the alcohol vapors would be exhausted through the volute collector into Lewis Research Center's

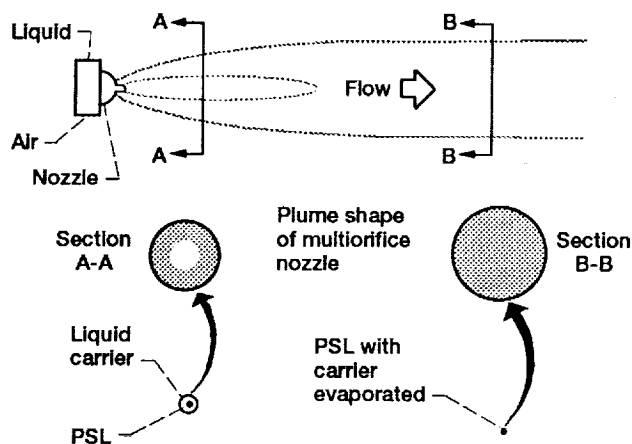


Figure 3.—Polystyrene latex seeding particle dispersion.

exhaust system, eliminating the need for a detector. It was, therefore, decided to install the spray nozzles in the plenum to eliminate any alcohol contamination in the test cell or clogging of the flow straightener.

As stated earlier, pressurized air was used to atomize the liquid as it was fed through the nozzles. The commercial nozzles purchased for this system dispensed the atomized mixture in a wide-angle, round spray pattern approximately 1 ft (0.3 m) in diameter in still atmospheric air at air-to-liquid pressures of 35 and 30 psig (241.3 and 206.8 kPa gage), respectively. Figure 3 shows a schematic of the dispersion and evaporation.

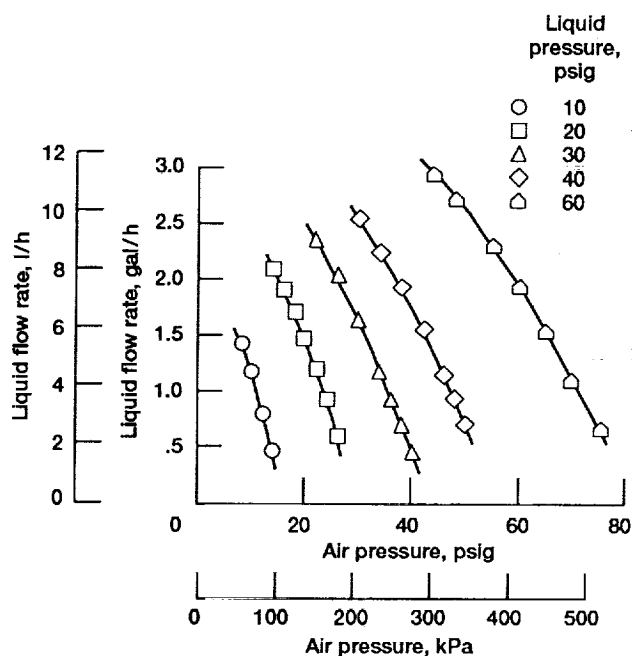


Figure 4.—Liquid flow rate at various air-to-liquid pressures.

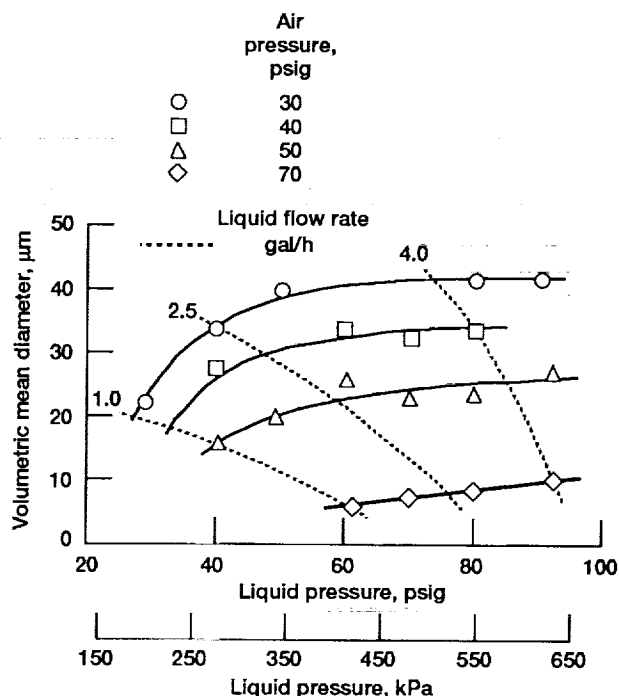


Figure 5.—Droplet size distribution at various liquid/air pressures.

The flow rate was controlled by changing the air-to-liquid pressure ratio as shown in figure 4. This information was obtained from the literature on the commercial nozzle used in this system. At constant liquid pressure, increasing the air pressure decreased the flow rate. However, the droplet size was controlled by changing both pressures. Increasing the pressure on the air and the liquid decreased the droplet size, thus, the droplets vaporized faster and contained fewer particles. Since the literature did not provide information on droplet size and distribution for various air and liquid pressures, tests were conducted with water by using one nozzle to determine values for volume mean diameter of the droplets in microns as defined by ASME E 799 (ref. 6). The volume mean diameter (VMD) is defined as the cube root of the sum of the number of particles multiplied by the particle diameters cubed and divided by the total number of particles. The VMD was used because it is sensitive to drop sizes below 20 μm , as shown in Tate (ref. 7). A total of 42 tests were conducted with pressures ranging from 10 to 90 psig (4.5 to 40.8 kPa gage) for air and 17 to 98 psig (7.7 to 44.4 kPa gage) for water. Figure 5 shows the results of these tests with the VMD plotted against liquid pressure at constant values of air pressure. Also plotted on this figure are three liquid flow rates of 1, 2.5, and 4 gal/h (4, 9.5, and 15 l/h). This figure illustrates the conditions that produce small droplets. The goal of the program was to obtain a good distribution of sufficiently small droplets to achieve total evaporation before reaching the compressor inlet. Throughout the rest of the test program, the desired flow rate through each nozzle was established at about 1 gal/h (4 l/h).

Seeder Development Test Data

As previously mentioned, measurements of the particle size distribution at the compressor inlet were sampled with a laser-based aerodynamic particle detector. Data were acquired for various conditions: samples of atmospheric air with and without flow through the compressor; samples with and without PSL seed particles in the liquid carrier; samples with the particle detector probe set at 25, 50, and 75 percent of the inlet span; and samples with the liquid carrier consisting of water only, 50 percent water/50 percent alcohol, and alcohol only. For the initial tests, the inlet bellmouth and air straightener were removed so that the spray pattern from the nozzles could be observed by a television camera mounted in front of the rig.

In this report, a representative sampling of the data is given and only at the 50-percent probe position at the compressor inlet. Table I shows a set of data generated from one sample with the particle detector that records the droplet size range and number for each bin. Figure 6 shows the distribution of droplet sizes in microns versus the particle count of each bin of the sample normalized by the particle count for the bin with the maximum number of particles. All the test data presented in this report are shown in this form. Test samples were acquired with and without air flowing through the compressor and with the seeder off to establish a baseline atmospheric particle size distribution. Sampling of this distribution was performed frequently to ensure that nothing had changed in the baseline data. The compressor flow rate during the first series of tests was below the compressor design conditions as a result of limitations on the facility drive motor.

TABLE I.—SAMPLE TAKEN FROM PARTICLE DETECTOR

Bin	Size, μm	Counts
1	0.09–0.11	8 429
2	0.11–0.15	13 658
3	0.15–0.20	12 994
4	0.20–0.25	6 663
5	0.25–0.30	3 116
6	0.30–0.40	2 488
7	0.40–0.50	1 424
8	0.50–0.65	4 797
9	0.65–0.80	1 174
10	0.80–1.00	1 380
11	1.00–1.25	2 819
12	1.25–1.50	2 833
13	1.50–2.00	5 787
14	2.00–2.50	3 158
15	2.50–3.00	1 293
16	> 3.00	555

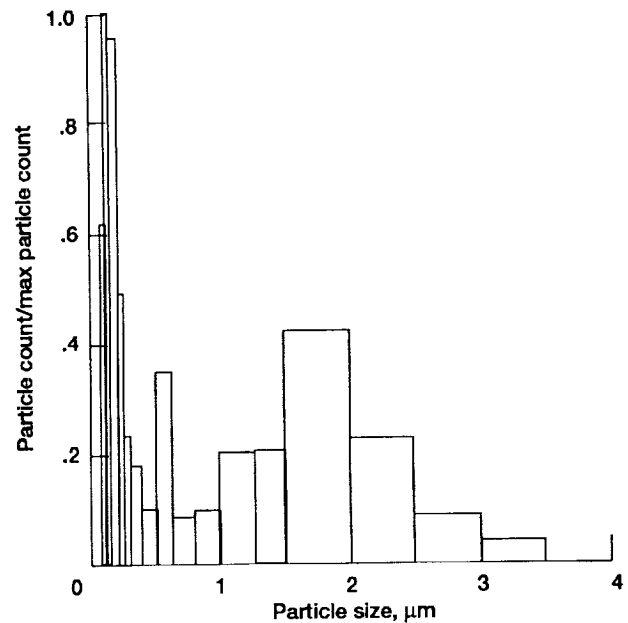


Figure 6.—Sample taken from particle detector.

Figure 7 shows the atmospheric particle size distribution from the particle detector with no flow and the seeder off. Only dust particles of about 0.2 μm or less were detected. The compressor was run at 45 lb/s (20.5 kg/s) airflow and another sample taken with the seeder off. Figure 8 shows the distribution of dust particles to be essentially the same. Results from figures 7 and 8 established the baseline data.

The initial tests with the seeder used water as the liquid carrier because of cost considerations. The seeder air pressure was set at 35 psig (241.3 kPa gage) and the liquid pressure at

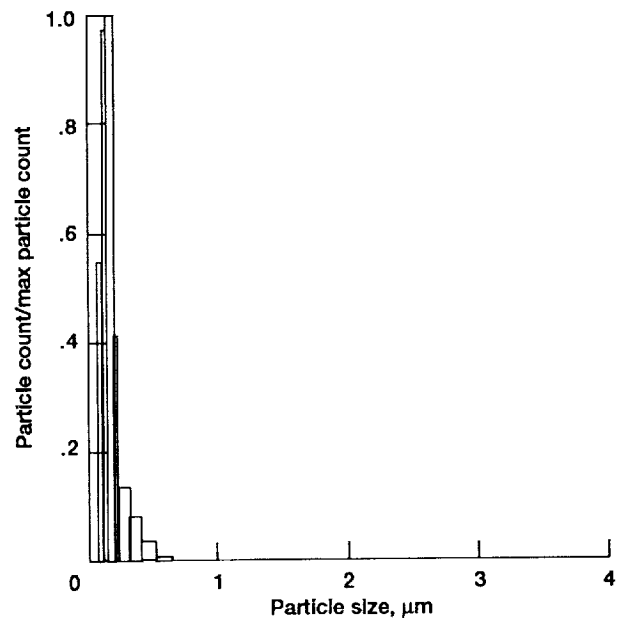


Figure 7.—Baseline sample taken upstream of Impeller; no flow; seeder off.

30 psig (206.8 kPa gage). From figure 5, this gave a droplet VMD of 19 μm . The same test conditions were established as previously mentioned and the seeder was turned on with no PSL in the water. The particle distribution (fig. 9) shows that much larger particles were detected, indicating that the water droplets had not completely evaporated before reaching the detector. During this period, the limitations on the facility drive motor were removed. Therefore, for the remainder of these tests, design conditions of 66.0 lb/s (30 kg/s) flow rate

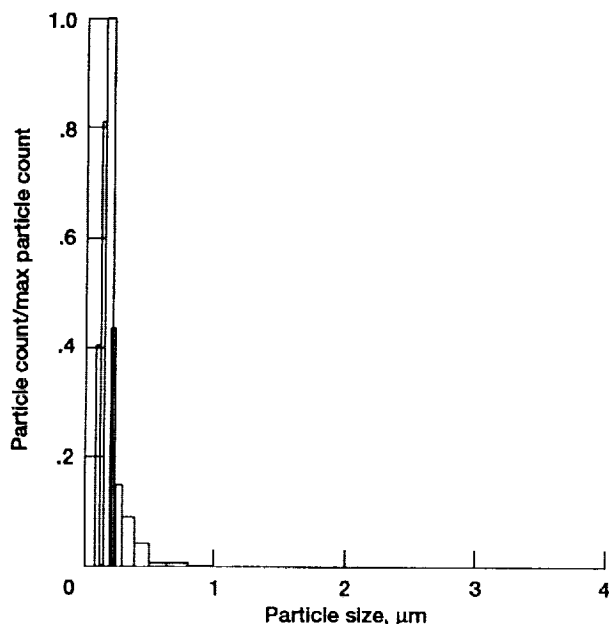


Figure 8.—Baseline sample taken upstream of impeller; with flow; seeder off.

were used. This higher flow rate decreases the particle residence time before reaching the compressor inlet and, thus, allows less time for the liquid carrier to evaporate.

To enhance the evaporation rate of the liquid carrier, ethyl alcohol was added to the water. A solution of 50 percent water/50 percent alcohol by volume without PSL was tested first. Figure 10 shows droplet sizes out to 3.3 μm , indicating that the liquid droplets had not completely evaporated. Also, the monitor showed that the incoming flow would not allow

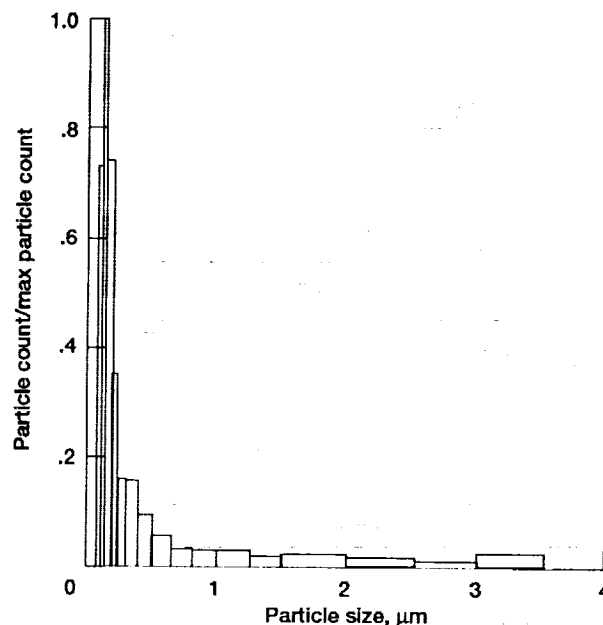


Figure 10.—Sample taken upstream of impeller; with flow; seeder on; 50 percent water/50 percent alcohol; no PSL.

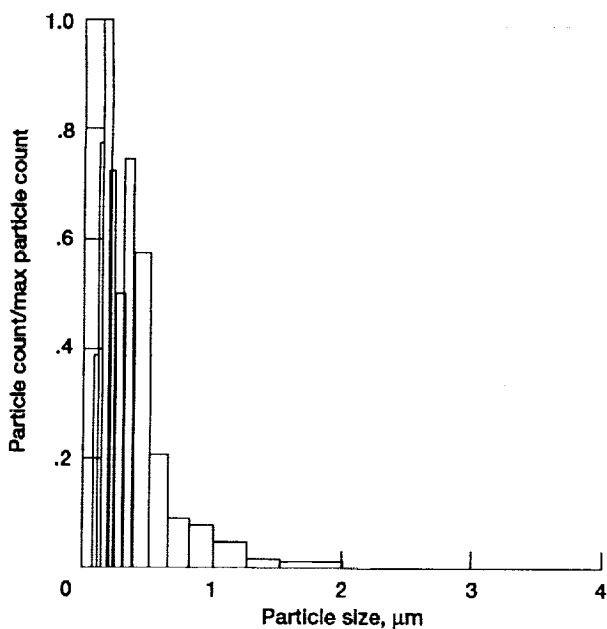


Figure 9.—Sample taken upstream of impeller; with flow; seeder on; 100 percent water; no PSL.

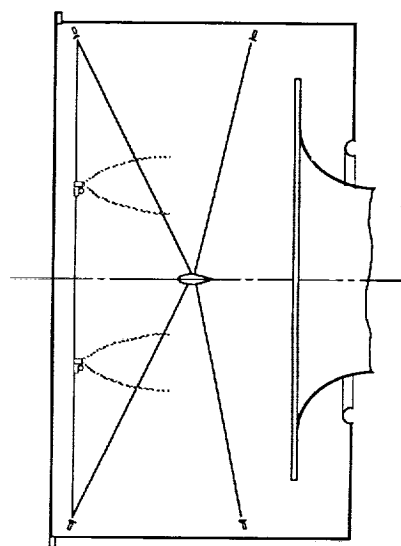


Figure 11.—Plenum with nozzles pointing downstream.

the spray pattern to form fully, but folded the spray back into a narrow cylinder. This increased the likelihood of the droplets coalescing to form larger drops. To correct this condition, the system was modified to locate the nozzles as far upstream as possible. New guy wires were installed at the front end of the plenum and the bars and nozzles were transferred to these wires. In addition, the nozzles were rotated 180° to face downstream as shown in figure 11. The air pressure in the seeder was increased to 40 psig (275.8 kPa gage), which gave

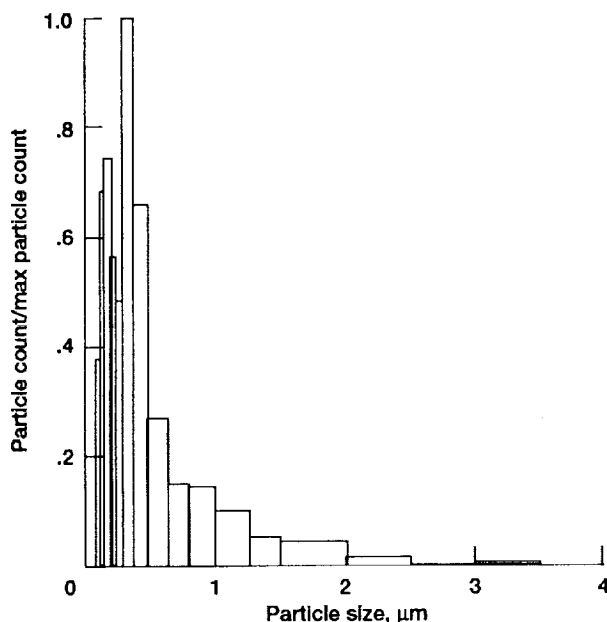


Figure 12.—Sample taken upstream of impeller; with flow; seeder on; 50 percent water/50 percent alcohol; no PSL.

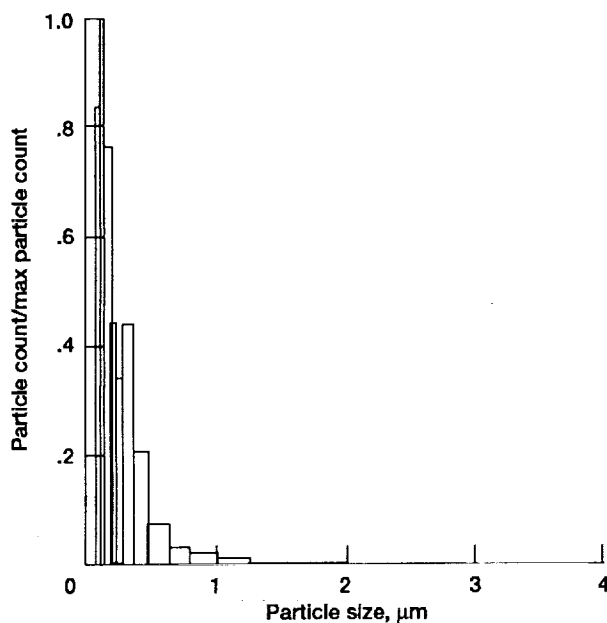


Figure 13.—Sample taken upstream of impeller; with flow; seeder on; 50 percent water/50 percent alcohol; no PSL.

a droplet VMD of 18 μm , and the test was repeated. Figure 12 shows an increase in droplet size below 2.0 μm and a decrease above 2.0 μm . The air and liquid pressures were increased to 45 and 40 psig (310.3 and 275.8 kPa gage), respectively. This increased the droplet VMD to 20. Figure 13 shows a marked improvement in reducing droplet size.

To improve evaporation further, alcohol only was used as the liquid carrier; the baseline data were checked again and showed no change. The air and liquid pressures were reset to 35 and 30 psig (241.3 and 206.8 kPa gage) and the seeder was turned on. Figure 14 shows that the alcohol was almost entirely evaporated. This satisfied the condition that the liquid carrier be fully evaporated before entering the test section. Because PSL was mixed with the alcohol, the resulting data includes PSL particles when referring to droplet size.

With the same aforementioned air and liquid pressures, the test was repeated with 15 ml/gal (4 ml/l) of 0.6- μm PSL in the alcohol. Figure 15 shows a marked increase in droplet size. However, it was discovered that the PSL used for this test had sat undisturbed for about a year and had agglomerated inside its container; therefore, it was not homogeneous when mixed with the alcohol. The contents of the tank were stirred to try to break down the large clumps of PSL into a more uniform mixture. The next test, shown in figure 16, has more of the large agglomerated PSL particles. This indicates that the stirring did not break down the clumps, but distributed the larger settled PSL particles throughout the alcohol.

Test results to this point required that the following changes be made:

(1) Because of the LSCC's low-speed environment (142 ft/s (43 m/s)), the initial requirement for small size seed-

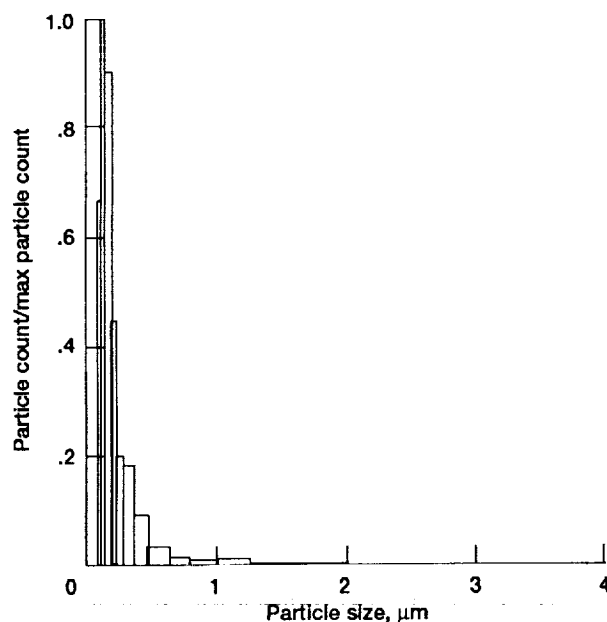


Figure 14.—Sample taken upstream of impeller; with flow; seeder on; 100 percent alcohol; no PSL.

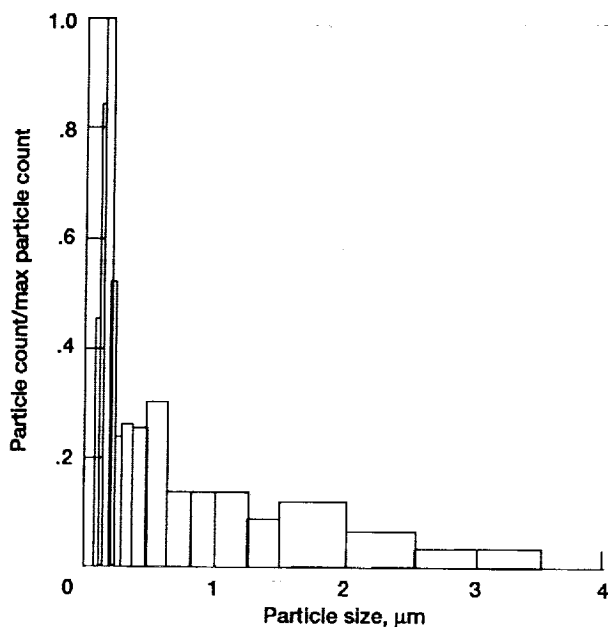


Figure 15.—Sample taken upstream of impeller; with flow; seeder on; 100 percent alcohol; 0.6 μm PSL.

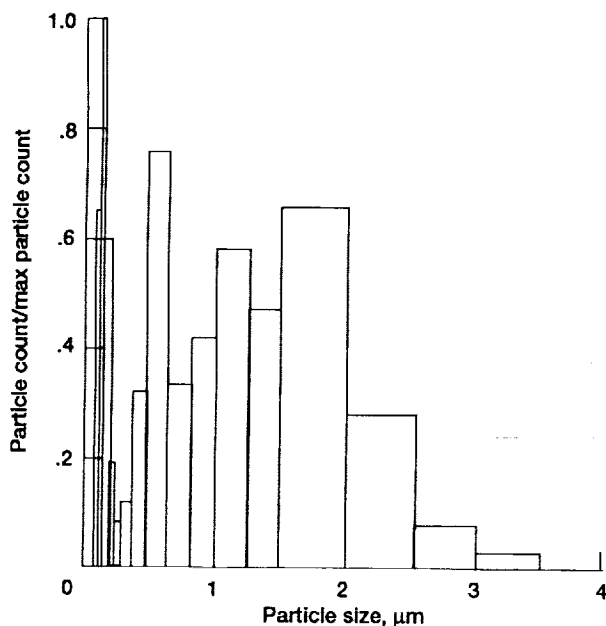


Figure 16.—Sample taken upstream of impeller; with flow; seeder on; 100 percent alcohol; 0.6 μm PSL; after stirring mixture.

ing was modified to use larger size seeding. Therefore, subsequent solutions of PSL were made in sizes that ranged from 0.85 to 1.1 μm . Because of the need to increase the volume of seed particles to provide adequate data rates, the amount of PSL used was increased to 30 ml/gal (8 ml/l) of alcohol. Before each test, the PSL was put in a blender for about 3 min before mixing with the alcohol to break apart any agglomerated PSL particles.

(2) For viewing the nozzles and spray pattern during research testing, a camera was located at the lower rear corner of the plenum. High-intensity lights were installed on the side of the plenum directed perpendicular to the flow (fig. 17). This allowed the inlet bellmouth and air straightener to be installed on the rig.

(3) The flexible tubing in the plenum was replaced periodically because of PSL buildup on the walls of the tubes, which restricted the liquid carrier flow. When using PSL in a test rig, one concern is the accumulation of seed particles on solid surfaces. During research testing with the compressor, this accumulation altered the blade surface and coated the window in the shroud. The latter degraded laser performance as a result of excess scattering of the laser beam off the window; thus, solid surfaces had to be cleaned daily.

A test check of the baseline data with these modifications incorporated showed no change in the atmospheric particle size distribution. A check was also made using the liquid carrier but with no PSL. The air and liquid pressures were set to 40 and 35 psig (275.8 and 241.3 kPa gage), respectively, which gave a droplet VMD of 21 μm , and the seeder was turned on with alcohol only. Again, good evaporation occurred as shown in figure 18. To achieve the smallest droplet size possible and still keep the flow rate at about 1 gal/h (4 l/h), the pressure on the air and liquid lines was increased to 70 and 60 psig (482.6 and 413.7 kPa gage), respectively. From figure 5, this would have given a droplet VMD of 9 μm . The test was repeated and figure 19 shows an even further reduction in droplet sizes above 0.6 μm . This last test, again, satisfied the requirement for obtaining complete evaporation of the liquid droplets before entering the compressor.

The final goal was for only single-size seed particles to be the dominant signature in the data taken from the particle detector. For the next series of tests, 30 ml/gal (8 ml/l) of blended 0.85- μm PSL were added to the alcohol. Baseline tests of no flow and flow with the seeder off showed the same results as before. The test results with the seeder on are shown in figure 20. Note the larger particles at about 3.3 μm . Since all of these tests occurred over time, a residue of PSL settled out in the bottom of the tanks. The tanks were emptied and cleaned, and a new solution of 0.85- μm PSL, blended for 5 min, was added to the alcohol. Blending time was later reduced to 2 min because of frothing of the PSL. In addition, for each 30 ml/gal of PSL blended, about 2 to 3 times that amount of alcohol was added to minimize frothing.

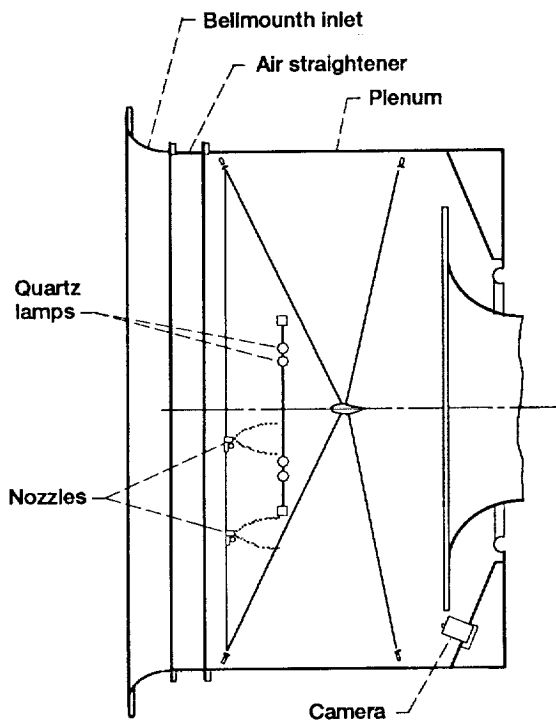


Figure 17.—Plenum with bellmouth inlet, air straightener, quartz lamps, and camera installed.

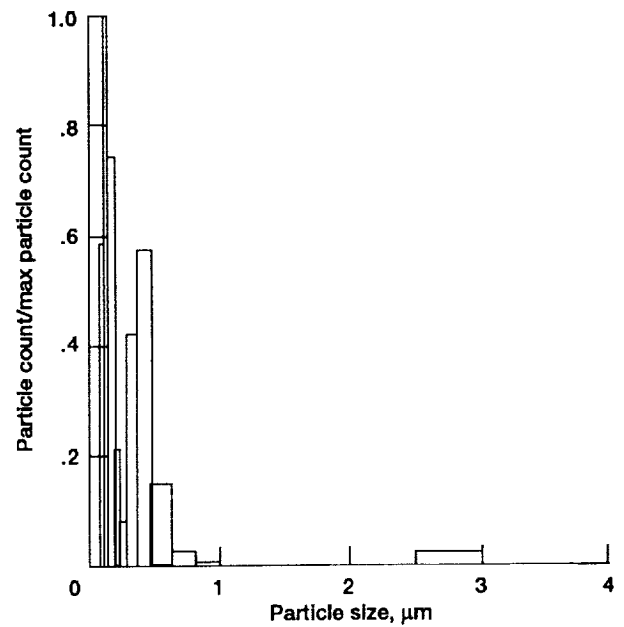


Figure 19.—Sample taken upstream of impeller; with flow; seeder on; 100 percent alcohol; no PSL; Increased air and liquid pressures.

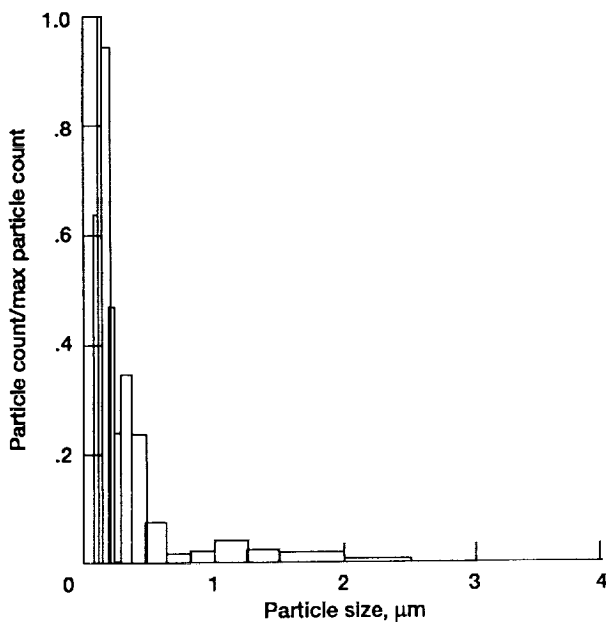


Figure 18.—Sample taken upstream of impeller; with flow; seeder on; 100 percent alcohol; no PSL.

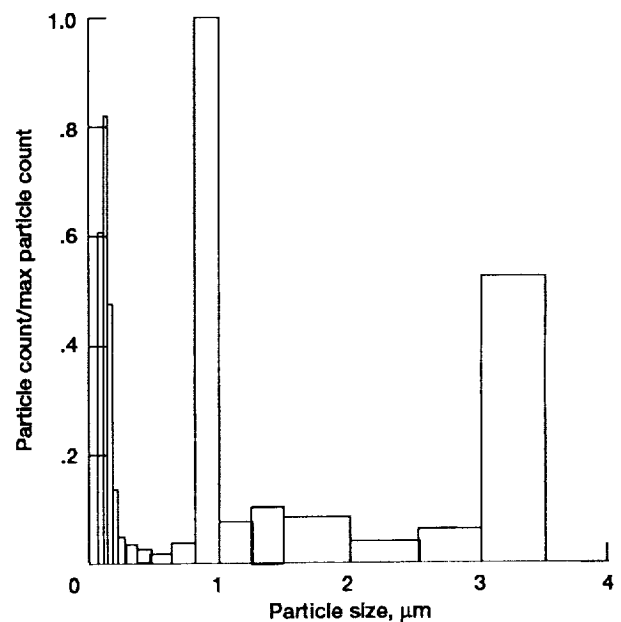


Figure 20.—Sample taken upstream of impeller; with flow; seeder on; 100 percent alcohol; 0.85 μm PSL.

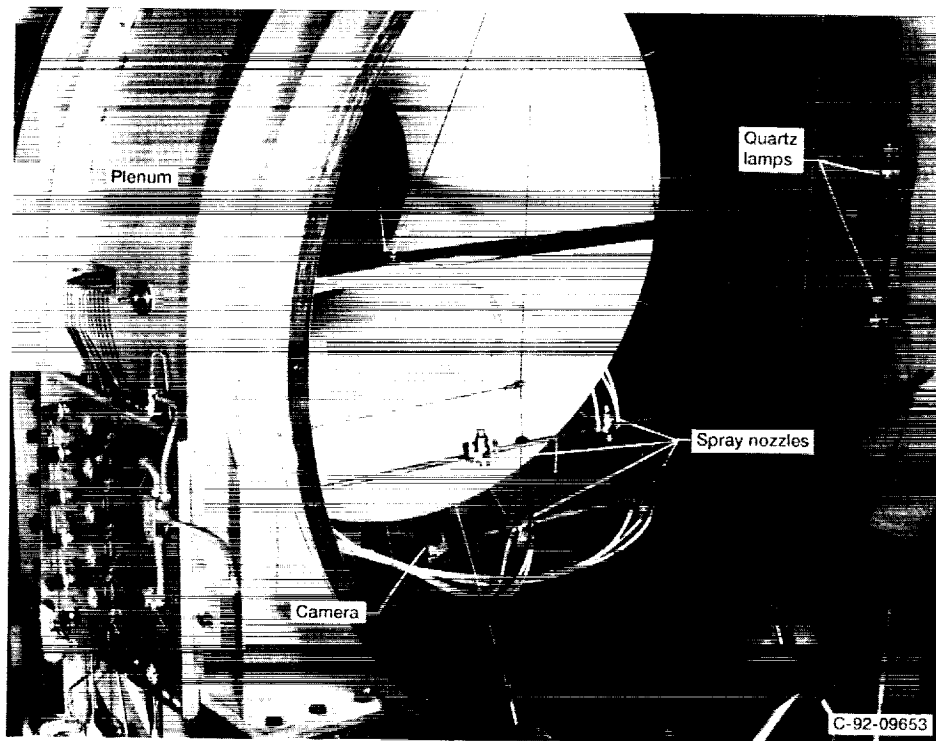


Figure 21.—Plenum with nozzles 10° forward of vertical.

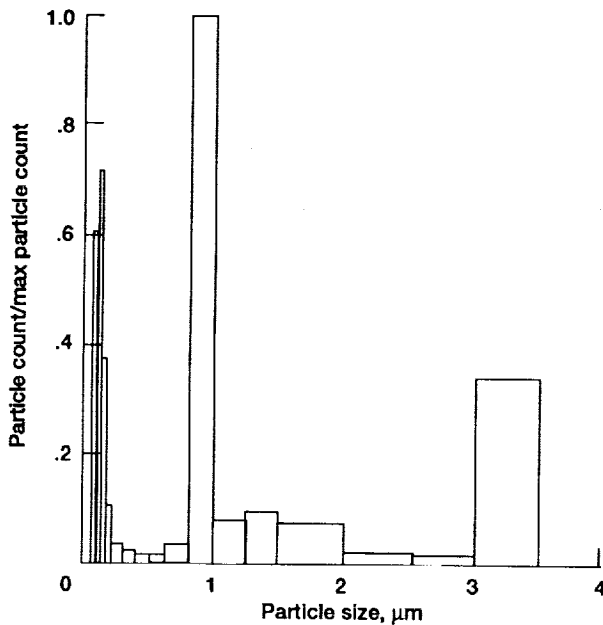


Figure 22.—Sample taken upstream of impeller; with flow; seeder on; 100 percent alcohol; 0.85 μm PSL; after nozzle adjustment.

To achieve a better spray pattern and minimize agglomeration of particles caused by the incoming flow, the top two nozzles were pointed down and inclined about 10° upstream, and the bottom two nozzles were pointed up and inclined about 10° upstream (fig. 21). Results show a reduction in the 3.3- μm particles (fig. 22). The nozzle positions were then adjusted perpendicular to the flow and the test was repeated. Figure 23 shows a continued reduction in the 3.3- μm size. The liquid pressure was decreased to 55 psig (379.2 kPa gage), which gave a droplet VMD of 8 μm . This test (fig. 24) resulted in single 0.85- μm particles entering the compressor with a negligible amount of particles above that size.

The final configuration for the adjustable seeder system included nozzles that were perpendicular to the flow, used 30 ml/gal of 0.85- μm blended PSL in an alcohol carrier, and had air/alcohol pressures of 70 and 55 psig (483.6 and 379.2 kPa gage), respectively.

As previously mentioned, all the testing reported herein used an aerodynamic particle detector that remotely sampled air from a 10-ft (3-m) length of 0.25-in. (6-mm) tubing connected to a 0.25-in. (6-mm) pitot tube immersed in the flow stream. As a result, there was a concern that the additional length of tubing from the sampling point to the particle detector had resulted in a false indication of complete evaporation of the liquid carrier. Therefore, a test was conducted with the laser velocimeter probe volume at the compressor inlet, with the seeders turned on, and without PSL. No signal output from

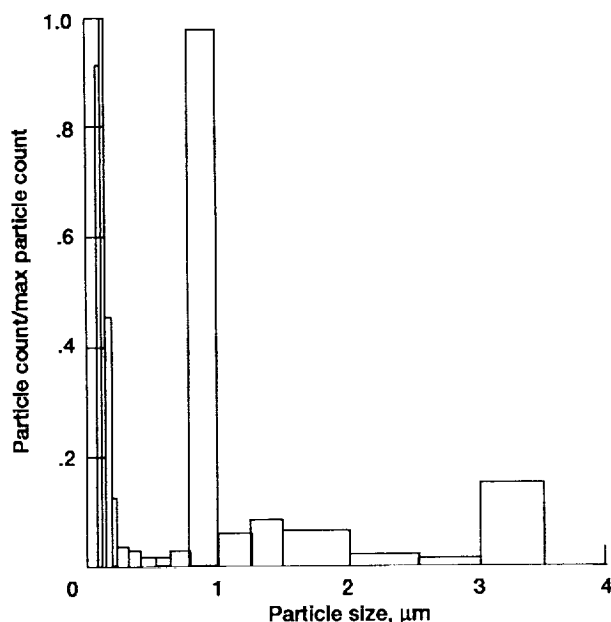


Figure 23.—Sample taken upstream of impeller; with flow; seeder on; 100 percent alcohol; 0.85 μm PSL; nozzles perpendicular to flow.

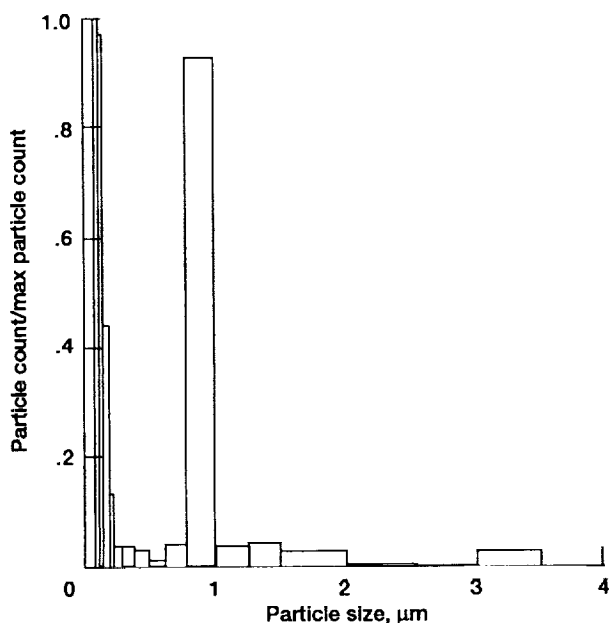


Figure 24.—Final sample taken upstream of impeller; with flow; seeder on; 100 percent alcohol; 0.85 μm PSL; decreased liquid pressure.

the laser velocimeter could be detected without PSL in the seed solution, verifying that the alcohol carrier had evaporated. The particle distribution was the same as that measured by the particle detector, as shown in figure 19. Reference 8 provides the results of the laser velocimeter investigations of the LSCC using the seeder system and reported herein.

A final modification was made during research operations by controlling the upper two nozzles and the lower two nozzles separately. This provided the necessary seeding in the area being probed by the laser while conserving alcohol use.

Concluding Remarks

An atomizer-based system for distributing high-volume rates of PSL seed material was developed to support laser velocimeter investigations of the NASA Low-Speed Centrifugal Compressor flow field. Complete evaporation of the liquid carrier before the flow entering the compressor was of primary concern for the seeder system design. The following are some of the lessons learned during the development of the seeding system.

1. The seed nozzle should incorporate a needle valve that can mechanically dislodge accumulated PSL seed material when the nozzle is turned off.

2. Water is less expensive as the liquid carrier and should be used whenever adequate residence times are available to ensure complete evaporation. As an alternative, ethyl alcohol and not methyl alcohol should be used since the latter dissolves PSL, is more toxic, and has a higher vapor pressure.

3. PSL agglomerates over time and needs to be mixed or blended before use. When blending, one should add 2 to 3 times the amount of the liquid carrier to the PSL solution to reduce or eliminate frothing. PSL will also settle out in the bottom of tanks and build up on the walls of tubing and solid surfaces such as blades and windows. Periodic cleaning of solid surfaces or replacement of tubing is necessary and should be done regularly.

4. Arrangement of the spray nozzles needs to be adjustable to provide maximum seeding at the laser probe volume. In this program, the nozzles provided a better spray pattern when set perpendicular to the flow. Operation was further enhanced by installing a camera in the plenum to view the spray pattern. Since the nozzles seed separate regions of the flow, putting the nozzles on separate on/off controls can conserve the seed and prolong run times.

During developmental testing, the final choice was made for 0.85- μm polystyrene latex (PSL) spheres as the seeding material and alcohol as the liquid carrier. Modifications were made to the seeding system until all alcohol was evaporated leaving only individual PSL seed particles in the airstream entering the compressor.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, June 25, 1993

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